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6. AUTHORS
Mark E. Campbell

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Cornell University
373 Pine Tree Road

Ithaca, NY 14850 -2820

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14. ABSTRACT
The aim of this research is to develop a unified theory for perception and planning in autonomous ground vehicles, with a specific focus on obstacle tracking/identification and trajectory planning, so as to enable reasoned, intelligent planning rather than simple reactive planning. This final report details our contributions. First, we developed a new method for anticipating obstacle motion using Gaussian Processes in order to enable contingency planning. Second, we developed three new mapping strategies including a unified terrain model based on a Markov Random Fields; soft relative maps; and fusion of stochastic maps. Third, we developed a methodology for capturing negative

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Report Title

Probabilistic Tracking and Trajectory Planning for Autonomous Ground Vehicles in Urban Environments

ABSTRACT

The aim of this research is to develop a unified theory for perception and planning in autonomous ground vehicles, with a specific focus on obstacle tracking/identification and trajectory planning, so as to enable reasoned, intelligent planning rather than simple reactive planning. This final report details our contributions. First, we developed a new method for anticipating obstacle motion using Gaussian Processes in order to enable contingency planning. Second, we developed three new mapping strategies including a unified terrain model based on a Markov Random Fields; soft relative maps; and fusion of stochastic maps. Third, we developed a methodology for capturing negative information (e.g. reasoning about areas where there is no sensor data), which is then used to improve tracking of obstacles. Fourth, we developed a new smoothing method which enables real time update of complex density functions (e.g. complex maps, tracking dynamic obstacles) in the presence of sparse data. We have published /accepted 23 journal articles and conference papers.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
03/05/2016	32.00	Daniel J. Lee, Mark E. Campbell. Smoothing Algorithm for Nonlinear Systems Using Gaussian Mixture Models, Journal of Guidance, Control, and Dynamics, (08 2015): 0. doi: 10.2514/1.G000603
03/05/2016	34.00	Nisar R. Ahmed, Mark Campbell, Rina Tse. Unified Terrain Mapping Model With Markov Random Fields, IEEE Transactions on Robotics, (04 2015): 0. doi: 10.1109/TRO.2015.2400654
03/05/2016	33.00	Kevin Wyffels, Mark Campbell. Negative Information for Occlusion Reasoning in Dynamic Extended Multiobject Tracking, IEEE Transactions on Robotics, (04 2015): 0. doi: 10.1109/TRO.2015.2409413
03/05/2016	35.00	J. Hardy, F. Havlak, M. Campbell. Multi-step prediction of nonlinear Gaussian Process dynamics models with adaptive Gaussian mixtures, The International Journal of Robotics Research, (06 2015): 0. doi: 10.1177/0278364915584007
03/05/2016	29.00	Frank Havlak, Mark Campbell. Discrete and Continuous, Probabilistic Anticipation for Autonomous Robots in Urban Environments, IEEE Transactions on Robotics, (04 2014): 0. doi: 10.1109/TRO.2013.2291620
08/27/2012	16.00	Isaac Miller, Mark Campbell. Sensitivity Analysis of a Tightly-Coupled GPS/INS System for Autonomous Navigation, IEEE Transactions on Aerospace and Electronic Systems, (04 2012): 1115. doi: 10.1109/TAES. 2012.6178052
08/27/2012	19.00	Isaac Miller, Mark Campbell, Dan Huttenlocher. Map-aided localization in sparse global positioning system environments using vision and particle filtering, Journal of Field Robotics, (09 2011): 0. doi: 10.1002/rob.20395
08/27/2012	17.00	C. Rivadeneyra, M. Campbell. Probabilistic multi-level maps from LIDAR data, The International Journal of Robotics Research, (01 2011): 0. doi: 10.1177/0278364910392405
08/27/2012	18.00	Jonathan R. Schoenberg, Mark Campbell, Isaac Miller. Posterior representation with a multi-modal likelihood using the gaussian sum filter for localization in a known map, Journal of Field Robotics, (03 2012): 0. doi: 10.1002/rob.20430
09/05/2013	23.00	Jason Hardy, Mark Campbell. Contingency Planning Over Probabilistic Obstacle Predictions for Autonomous Road Vehicles, IEEE Transactions on Robotics, (08 2013): 0. doi: 10.1109/TRO.2013.2254033

TOTAL: **10**

Number of Papers published in peer-reviewed journals:

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<u>Received</u> <u>Paper</u>

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(c) Presentations

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
03/05/2016	30.00	Frank Havlak, Jason Hardy, Mark Campbell. Multiple-step prediction using a two stage Gaussian Process model, 2014 American Control Conference - ACC 2014. 04-JUN-14, Portland, OR, USA. : ,
08/27/2012	11.00	Daniel Lee, Mark Campbell. Iterative Smoothing Approach using Gaussian Mixture Models for Nonlinear Estimation, IEEE/RSJ International Conference on Intelligent Robots and Systems. 20-SEP-12, . : ,
08/27/2012	15.00	Rina Tse, Nisar Ahmed, Mark Campbell. Unified Mixture-Model Based Terrain Estimation with Markov Random Fields, IEEE International Conference on Multisensor Fusion and Integration. 13-SEP-12, . : ,
08/27/2012	14.00	Brandon Jones, Mark Campbell, Lang Tong. Bipartite Matching of Stochastic Maps, Allerton Conference on Communication, Control, and Computing. 10-OCT-11, . : ,
08/27/2012	13.00	Mark Campbell, Lang Tong, Brandon Jones. Consensus of stochastic maps with nearest neighbor interactions, SPIE Defense, Security, and Sensing. 16-APR-12, . : ,
08/27/2012	12.00	Nisar Ahmed, Jon Schoenberg, Mark Campbell. Fast Weighted Exponential Product Rules for Robust General Multi-Robot Data Fusion, Robotics Science and Systems Conference. 09-JUL-12, . : ,
08/31/2011	7.00	J. Hardy, M. Campbell. Clustering Obstacle Predictions to Improve Contingency Planning for Autonomous Road Vehicles in Congested Environments, IEEE/RSJ International Conference on Intelligent Robots and Systems, . 25-SEP-11, . : ,
09/05/2013	27.00	Mark McClelland, Mark Campbell, Tara Estlin. Qualitative Relational Mapping for Robotic Navigation, Infotech. 06-JUN-12, . : ,
09/05/2013	28.00	Kevin Wyffels, Mark Campbell. Modeling and Fusing Negative Information For Dynamic Extended Multi-object Tracking, IEEE International Conference on Robotics and Automation. 06-JUN-13, . : ,
09/05/2013	20.00	Nisar Ahmed, Mark Campbell, Rina Tse. Unified mixture-model based terrain estimation with Markov Random Fields, 2012 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI 2012). 13-SEP-12, Hamburg, Germany. : ,
09/05/2013	21.00	Daniel J. Lee, Mark E. Campbell. Iterative smoothing approach using Gaussian mixture models for nonlinear estimation, 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2012). 07-OCT-12, Vilamoura-Algarve, Portugal. : ,
09/05/2013	22.00	Mark Campbell, Lang Tong, Brandon Jones. Consensus of stochastic maps, SPIE Defense, Security, and Sensing. 01-APR-12, Baltimore, Maryland. : ,
09/05/2013	24.00	Jonathan Schoenberg, Mark Campbell, Nisar Ahmed. ast Weighted Exponential Product Rules for Robust General Multi-Robot Data Fusion, Robotics: Science and Systems. 06-JUN-12, . : ,

TOTAL: 13

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
08/27/2012	8.00	Nisar Ahmed, Mark Campbell. Fast Consistent Chernoff Fusion of Gaussian Mixtures for Ad Hoc Sensor Networks, IEEE Transactions on Signal Processing (01 2012)
08/27/2012	9.00	Isaac Miller, Mark Campbell. Sensitivity Study of a Tightly-Coupled GPS / INS System for Autonomous Navigation, IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS (04 2012)
08/31/2011	1.00	I. Miller and M. Campbell and D. Huttenlocher. Particle Filtering for Map-Aided Localization in Sparse GPS Environments, Journal of Field Robotics (08 2011)
08/31/2011	6.00	J. Schoenberg, M. Campbell, I. Miller. Posterior Representation with a Multi-Modal Likelihood Using the Gaussian Sum Filter, Journal of Field Robotics (08 2011)
08/31/2011	5.00	I. Miller, M. Campbell, D. Huttenlocher. Map-Aided Localization in Sparse GPS Environments using Vision and Particle Filtering, Journal of Field Robotics (08 2011)
08/31/2011	4.00	César Rivadeneyra, Mark Campbell. Probabilistic multi-level maps from LIDAR data, The International Journal ofRobotics Research (01 2011)
08/31/2011	3.00	M. Campbell. Intelligent Autonomy in Robotic Systems, The Bridge, Quarterly of the NAE (01 2010)
09/05/2013	26.00	Brandon Jones, Mark Campbell, Lang Tong. Maximum Likelihood Fusion of Stochastic Maps, IEEE Transactions on Signal Processing (12 2012)
09/05/2013	25.00	Frank Havlak, Mark Campbell. Discrete and Continuous, Probabilistic Anticipationfor Autonomous Robots in Urban Environments, IEEE Transactions on Robotics (12 2012)

TOTAL: 9

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Books

Received   Book

TOTAL:

Received   Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

• John A. Mellowes '60 Professor of Mechanical and Aerospace Engineering, 2015
• AIAA Best Paper Award, AIAA Guidance Navigation and Control Conference, 2012
• Defense Sciences Study Group (DSSG), 2012-2013
• Best Conference Poster Award, Int'l Symposium on Distributed Autonomous Robotic Systems, 2012.
• National Academy of Sciences, Distinctive Voices Series, Irvine CA, 2012.
• Kavli Fellow, National Academy of Science, 2011.
• National Academy of Engineering Frontiers in Engineering Symposium, Invited Speaker, 2010.
• Douglas Whitney Excellence in Teaching Award, Cornell University, 2010.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Jason Hardy	0.40	
Brandon Jones	0.40	
Daniel Lee	0.20	
Mark McClelland	0.20	
Kevin Wyffels	0.40	
FTE Equivalent:	**1.60**	
Total Number:	**5**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Mark Campbell	0.15	
FTE Equivalent:	**0.15**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Scott Schlacter	0.40	Mechanical Engineering
FTE Equivalent:	**0.40**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 5.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 1.00

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The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Jason Hardy	
Frank Havlak	
Kevin Wyffels	
Mark McClelland	
Total Number:	**4**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Obstacle Anticipation using Gaussian Processes
This paper presents an adaptive Gaussian Mixture Model (aGMM) formulation for performing multiple-step probabilistic state predictions using a nonparametric Gaussian Process (GP) regression model. The presented prediction algorithm is applicable to any dynamic system that is challenging to model parametrically, but where data is available. Gaussian mix- ture elements are propagated through the GP by analytically evaluating expectation integrals for the moments of the out- put distribution. Two metrics are presented and compared for adaptively splitting the initial state distribution into a sum of Gaussians to reduce the effect of nonlinearities on prediction accuracy: (1) an analytical evaluation of the excess kurto- sis which measures the non-Gaussianity of the output distribution, and (2) a weighted least-squares regression model which evaluates the local nonlinearity of the GP mapping with respect to the input distribution. In addition, an on-the-fly data selection method is presented to reduce the computational complexity associated with analytically evaluating the higher-order moments of the GP output distribution. The proposed adaptive GP-aGMM formulation is applied to the case of anticipating driver behavior at road intersections using a GP driver behavior model in combination with a parametric vehicle model. Prediction performance for this scenario is evaluated using driving data collected from three human sub- jects navigating a standard four-way intersection. Results demonstrate that the presented prediction algorithm is capable of accurately capturing multimodal behavior in the GP training data.

Negative Information
A novel approach to utilize negative information to improve the precision and accuracy of extended multiobject track- ing is presented. The parameterized probability density of object tracks undetected in sensor data is updated via inferences about the conditions necessary to result in occlusion of the undetected object. Negative information is also leveraged to inform track ex- istence and data association, both of which contribute to a more sensible belief of the local dynamic scene. Simulation and experi- mental results are presented from autonomous driving scenarios, demonstrating that the use of negative information leads to a more complete, accurate, precise, and intuitive belief of the local scene, enabling high-level tasks that would otherwise be impractical.

Contingency Planning
This paper presents a novel optimization based path planner capable of planning multiple contingency paths to directly account for uncertainties in the future trajectories of dynamic obstacles. This planner addresses the particular problem of probabilistic collision avoidance for autonomous road vehicles that are required to safely interact, in close proximity, with other vehicles with unknown intentions. The presented path planner utilizes an efficient spline based trajectory representation and fast but accurate collision probability bounds to simultaneously optimize multiple continuous contingency paths in real-time. These collision probability bounds are efficient enough for real- time evaluation, yet accurate enough to allow for practical close- proximity driving behaviors such as passing an obstacle vehicle in an adjacent lane. An obstacle trajectory clustering algorithm is also presented to enable the path planner to scale to multiple- obstacle scenarios. Simulation results show that the contingency planner allows for a more aggressive driving style than non- contingency based approaches without compromising the overall safety of the robot.

Probabilistic Mapping
A terrain mapping model is proposed using a generalized Markov Random Field (MRF) representation. Unlike previous work, the proposed MRF can fully represent uncer- tainties due to sensor pose and measurement errors, as well as data association errors in a single model. Additionally, neither homoscedasticity nor a predefined shape of the likelihood distri- bution is assumed. The flexibility of an MRF model allows spatial height correlations to be incorporated. The ability to include spatial correlations not only improves the accuracy through the benefits of Bayesian prior modeling, but also serves as a basis for terrain property characterization. Maximum likelihood solutions of terrain roughness are derived. Benefits of the proposed model are demonstrated experimentally on indoor and outdoor datasets. Results show that the MRF model leads to lower height estimation errors. In addition, the capability of estimating non-Gaussian height distributions allows the information about individual terrain features to be preserved. Finally, the model is able to accurately estimate the roughness of the terrain, which is beneficial for edge detection of obstacles and non-traversible terrain regions.

Relative Mapping
This work develops a novel method for autonomous robotic navigation and mapping of large scale spaces with sparse landmarks and minimal sensing. The proposed algorithm constructs a graph-based map which encodes the relative location of landmarks in the environment. Uncertainty in these locations is captured by imposing qualitative constraints on the relationships between landmarks observed by the robot. These relationships are represented in terms of the relative geometrical layout of landmark triplets. A novel measurement method based on camera imagery is presented which extends previous work from the field of Qualitative Spatial Reasoning. Measurements are fused into the map using a deterministic approach based on iterative graph updates. Algorithm performance is evaluated using a combination of experimentally collected vision data and Monte-Carlo simulations.
Smoothing for improved perception and robustness in planning
A smoothing method for nonlinear systems using Gaussian mixture models is pre- sented. Problems of interest include applications with highly nonlinear dynamics and/or measurement models, and sparse measurements. Two new smoothing meth- ods are presented which incorporate adaptive Gaussian splitting in the forward path, and condensation in the backward path. A nonlinear forward-backward smoothing algorithm with Gaussian mixture models is also enabled by a novel technique to

esti- mate the `backward corrector'. An experiment of a robot performing indoor naviga- tion in a sparse featured environment demonstrates the performance of the smoothing algorithms in typical applications. Experimental results demonstrate that the new smoothing algorithms give more accurate and consistent estimates than a traditional Kalman smoother, even in the presence of a sparse featured environment and sparse measurements.

Fusion of stochastic maps
The fusion of independently obtained stochastic maps by collaborating mobile agents is considered. The proposed approach includes two parts: generalized likehood ratio matching and maximum likelihood alignment. In particular, an affine invariant hypergraph model is constructed for each stochastic map and a bipartite matching via a linear program is used to establish landmark correspondence between stochastic maps. A maximum likelihood alignment procedure is proposed to estimate rotation, translation and scale parameters in order to construct a global map of the environment. A main feature of the proposed approach is its scalability with respect to the number of landmarks: the matching step has polynomial complexity and the maximum likelihood alignment solution is obtained in closed form. Experimental validation of the proposed fusion approach is performed using the Victoria Park experimental benchmark.

Technology Transfer

Concepts and papers from our work were regularly delivered to industry, particularly the automobile industry and the Army Research Lab, over the years of the project. This includes the probabilistic anticipation, contingency planning, and negative information work. In addition, PhD students graduated and are working for Tesla, Nissan, Bosch, and Ford.